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Article

Evaluating Litter Yield and Decomposition for Re-Vegetated Mangroves in a Subtropical Mudflat

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**Featured Application:** The findings obtained from this study have implications for global blue carbon budgeting.

Abstract: Field monitoring and incubation experiments were conducted to evaluate the litter yield and examine the decomposition of the litter of three representative mangrove species frequently used for mangrove re-vegetation in a subtropical mudflat on the South China coast. The results show that the litter yield of the investigated mangrove species varied significantly from season to season. The annual litter production was in the following decreasing order: *Heritiera littoralis* > *Thespesia populnea* > *Kandelia obovata*. Initially, rapid decomposition of easily degradable components of the litter materials resulted in a marked weight loss of the mangrove litter. There was a good linear relationship between the length of field incubation time and the litter decomposition rate for both the branch and the leaf portion of the three investigated mangrove species. Approximately 50% or more of the added mangrove litter could be decomposed within one year and the decomposed litter could be incorporated into the underlying soils and consequently affect the soil carbon dynamics. An annual soil carbon increase from 2.37 to 4.64 g/kg in the top 5 cm of the soil was recorded for the investigated mangrove species.

Keywords: mangrove; litterfall; litter decomposition; soil carbon sequestration; subtropical coast

1. Introduction

Mangrove wetlands play an important role in the provision of ecosystem services [1–3]. Rapid coastal development in the past few decades has led to a large-scale destruction of mangroves around the world [4], with its adverse impact on coastal ecosystems becoming more and more evident [5,6]. To halt further ecological degradation in tropical and subtropical estuarine areas, re-vegetation of mangroves is thought to be an effective measure in addition to mangrove wetland conservation [7–9]. However, replanting mangrove trees in tidal zones is more challenging and usually involves larger capital and labor inputs, as compared to re-vegetation of terrestrial lands.

The economic viability of a mangrove re-vegetation project needs to be carefully evaluated based on a sound cost–benefit analysis. Carbon credit is among the major benefits from restoration of mangrove wetlands [10]. While carbon being stored in the living parts of mangrove trees is important, carbon storage in mangrove soils plays an even more important role in carbon sequestration [11,12]. Due to anaerobic conditions encountered in tidal zones, decomposition of mangrove litters is relatively slow [13,14]. Therefore, mangrove soils/sediments tend to contain more organic carbon as compared to many terrestrial forest soils [15,16].

The potential of mangroves to contribute to tidal soil/sediment carbon credit is determined by the difference between carbon input and carbon output [17]. Litter production of mangroves is the primary source of organic carbon input in mangrove wetlands while decomposition of mangrove litters and the associated release of carbon-containing gases is the major pathway through which soil carbon is lost. Therefore, there is a need to understand the litter yield of mangroves and the decomposition of litter in the mangrove soils in order to evaluate the capacity of replanted mangrove trees to sequester atmospheric carbon dioxide (CO₂) and store the captured carbon in the tidal soils/sediments.

Due to varying physiographic conditions and the difference in mangrove species, the yield of mangrove litter could vary markedly from location to location, with a range of 170–5384 g/m² [18]. Similarly, the decomposition rate of mangrove litter is also highly variable and depends on environmental conditions such as temperature, salinity, and redox potential [14]. While there has been increasing research done to examine mangrove litter yield and in-soil decomposition, many efforts have been focused on natural mangroves in tropical and subtropical climatic zones [19–22] with insufficient work being done for replanted mangroves.

Barren tidal mudflats are widespread on the subtropical South China coast [23] and can be potentially used for planting mangroves. The objective of this study was to examine the litter yield and decomposition for mangrove species that are suitable for being grown on the South China coast in order to obtain useful information that can be used for evaluating the potential contribution of mangrove re-vegetation to soil carbon sequestration in the South China coastal areas.

2. Materials and Methods

2.1. Selection of Study Site

A representative site was selected for this study. The study area is part of the Qi'ao Island Nature Reserve (113°36'–113°39' E, 22°23'–22°27' N) located on the west side of the Pearl River Estuary, China, with an area of about 23.8 km² (Figure 1). The study area experiences a subtropical monsoon climate with an average annual temperature of 22.5 °C and an average annual rainfall of 2061.9 mm. Since 1999, large-scale mangrove re-vegetation was carried out within the study area. Currently, at least 15 species of mangrove plants are identified in the study area with *Kandelia obovata* (Linn.) Druce, *Heritiera littoralis* (Dryand) Ait., and *Thespesia populnea* (L.) Soland. ex Corr being the dominant species. The tidal sediments/soils consisted of fine materials without gravel.

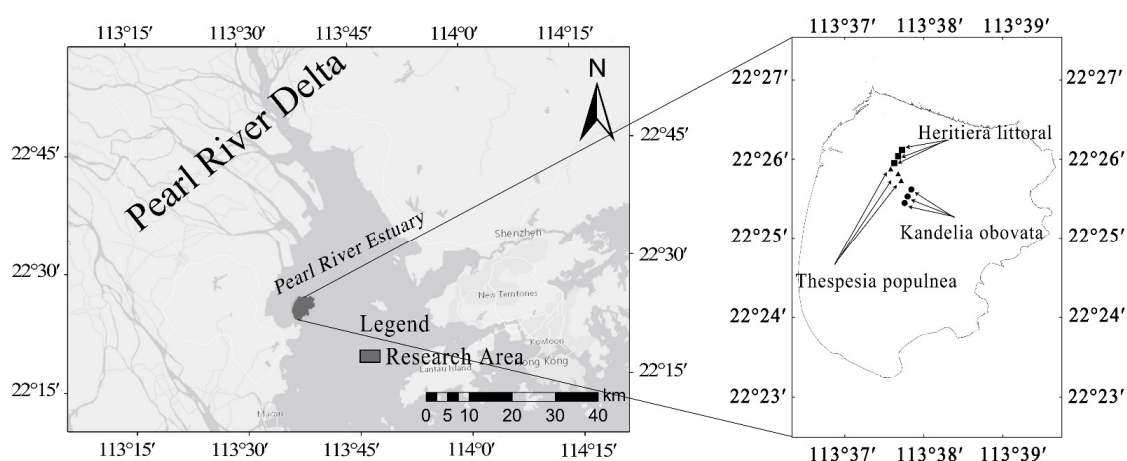


Figure 1. Location map of the study area showing the sampling sites.

2.2. Field Investigation and Sample Collection

2.2.1. Monitoring of Litterfall

Monitoring of litter yield was focused on the three dominant mangrove species (i.e., *Kandelia obovata* (Linn.) Druce, *Heritiera littoralis* (Dryand) Ait., and *Thespesia populnea* (L.) Soland. ex Corr). For each species, three random sample plots (10 m × 10 m) were used; their locations are indicated in Figure 1. The basic growth characteristics of the investigated mangrove trees in the sample plots are given in Table 1.

Table 1. The basic growth characteristics of the investigated mangrove trees.

Plant Species	Average DBH * (cm)	Average Height (m)	Crown (m × m)	Clear Stem (cm)	Age (year)
<i>Kandelia obovata</i>	10.35 ± 1.12	3.5 ± 0.5	2.1 × 2.3	90	10
<i>Heritiera littoralis</i>	15.37 ± 3.89	5.5 ± 0.5	2.4 × 2.1	70	9
<i>Thespesia populnea</i>	9.18 ± 2.95	3.7 ± 0.5	1.7 × 1.6	50	7

* DBH: diameter at breast height.

The monitoring was carried out from September 2013 to August 2014. Three litterfall traps were randomly placed in each of the nine sample plots. The litterfall collection unit was made up of a square wooden frame (1 m × 1 m) and a nylon mesh bag (pore size: 1 mm) attached to the frame. The litterfall collector was hung under the tree with the bottom being about 0.3 m above the ground. Litterfall was collected monthly. The litters in each collection unit were packed in a plastic bag, transported to the laboratory, and oven-dried at 60 °C until constant weight was obtained. The dried litter biomass was then obtained by weighing.

2.2.2. Litter Decomposition Experiment

A field experiment was also conducted during the period from September 2013 to August 2014 to examine the decomposition of litters for the three dominant mangrove species. Prior to the experiment, samples of fresh branches and leaves for each of the three species were collected from the study site. In the laboratory, the fresh litter samples were oven-dried at 60 °C until constant weight. A tightly fastened nylon mesh bag with a pore size of 1 mm was used to hold a mixture of leaf sample (10 g) and branch sample (10 g). For each of the 10 m × 10 m plots, three random locations were used, representing three replicates within the experimental plot. For each location within the plot, 12 bags with the loaded leaves and branches were laid on the ground surface.

During the period of the field experiment, one of the 12 litter sample bags was removed at the end of each month and transported to the laboratory to determine the weight loss.

2.2.3. Monitoring of Soil Carbon Change

Samples of soil immediately below the litter bags were also collected on four occasions (i.e., at the end of November 2013, February 2014, May 2014, and August 2014) to monitor the seasonal change in soil carbon content as affected by the decomposing litters. The soil samples were taken from the surface soil layer (0–5 cm) using a stainless steel soil corer. After collection, the soil samples were transported to the laboratory within 24 h and ground to pass through a 2 mm sieve after air-drying. The ground soil samples were stored in sealed plastic bags prior to analysis.

2.3. Laboratory Analysis

The weight loss of leaf and branch portions was determined separately by weighing after washing with water and oven-drying at 60 °C until constant weight. The organic carbon contained in the soils was determined by a modified Walkley–Black method [24]. Briefly, 0.2 g of the ground soil sample (<0.149 mm) was digested with a mixed potassium dichromate and sulfuric acid solution in an oil bath (220–230 °C) for 5 min prior to titration with a standardized ferrous sulfate solution using

1,10-Phenanthroline monohydrate as the indicator. The organic carbon content was then estimated from the amount of potassium dichromate being consumed during the reaction.

2.4. Statistical Analysis Methods

The data were analyzed by the SAS Visual Investigator software for the difference between groups (Duncan method), and the data were subjected to regression analysis and mapping using Origin 2019.

2.5. Calculation of Litter Weight Loss Rate and Soil Carbon Storage

The weight loss rate (WLR) of the added mangrove litter during a given period of field incubation was calculated by the following formula:

$$\text{WLR (\%)} = (W_0 - W_i) / W_0 \times 100 \quad (1)$$

where W_0 stands for the initial dried biomass of litter sample placed on the soil and W_i denotes the dried biomass of the decomposing litter sample collected after Day i since commencement of the field incubation.

The carbon storage in the soil under different types of mangrove species was estimated using the method recommended by the Technical Specification Writing Group for Ecosystem Carbon Sequestration Projects [25].

3. Results

3.1. Litterfall Variation of the Three Selected Mangrove Species during the Monitoring Period

The dried biomass of the three selected mangrove species that was obtained at the end of each month during the period of study from September 2013 to August 2014 is given in Figure 2. Although all three species tended to have a high litter yield period from September to November and a low litter yield period from January to March, different variation patterns were observed for the different mangrove species. For *Thespesia populnea* (L.) Soland. ex Corr., There was only one single peak with a value of $122 \pm 9.04 \text{ g/m}^2$ in October. Litter yield then decreased and remained at a low level during the period February to August. For *Heritiera littoralis* (Dryand) Ait., the litter yield increased after March and reached a second peak in June. *Kandelia obovata* (Linn.) Druce also had a peak in June.

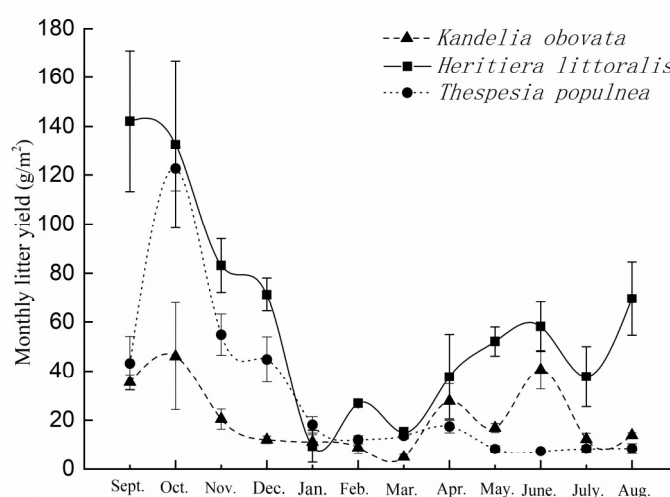


Figure 2. The monthly change in litter yield of the three mangrove species.

3.2. Litter WLR of the Three Mangrove Species over Varying Lengths of Field Incubation

The WLR of either the branch or leaf following different lengths of field incubation for the three mangrove species is shown in Table 2. In general, the WLR increased with an increasing length of incubation though a higher calculated WLR for shorter periods of incubation, relative to that for longer periods of incubation, was observed on some occasions, e.g., the 30 days versus 60 days for *Heritiera littoralis* (Dryand) Ait. (branch and leaf) and *Thespesia populnea* (L.) Soland. ex Corr (branch).

Table 2. Calculated weight loss rate (%) of the leaf and branch portions for the three selected mangrove plant species.

Time (d)	Branch <i>Heritiera</i>	Leaf <i>Heritiera</i>	Branch <i>Thespesia</i>	Leaf <i>Thespesia</i>	Branch <i>Kandelia</i>	Leaf <i>Kandelia</i>
30	9.18 ± 1.42gh	19.76 ± 3.81f	10.57 ± 2.55g	15.67 ± 1.16f	3.14 ± 1.1f	14.9 ± 1.31g
60	6.59 ± 2.61h	11.18 ± 1.54g	8.41 ± 2.7g	16.43 ± 1.24f	4.97 ± 1.1f	16.27 ± 2.02g
90	11.65 ± 1.21g	12.24 ± 1.69g	15.29 ± 1.52f	26.11 ± 2.07e	14.51 ± 2.63e	14.02 ± 2.16g
120	19.27 ± 1.71f	16.24 ± 1.51f	20.64 ± 1.41e	25.86 ± 1.8e	13.14 ± 2.7e	20.98 ± 1.02f
150	24.71 ± 1.25e	30.35 ± 2.01e	22.04 ± 1.41e	30.06 ± 1.27d	21.7 ± 1.07d	25.98 ± 1.1e
180	26 ± 2.48e	24.12 ± 3.84d	32.36 ± 2.18d	37.71 ± 1.2c	22.84 ± 1.06d	25.29 ± 1.41e
210	34 ± 2.98cd	34.82 ± 1.83c	23.82 ± 3.45e	29.94 ± 3.71d	20.78 ± 2.59d	26.47 ± 1.19e
240	32.35 ± 3.46d	37.76 ± 1.55c	38.6 ± 1.36c	36.18 ± 1.04c	33.04 ± 2.78c	35.29 ± 1.04d
270	36.65 ± 1.42c	43.53 ± 2.07b	31.72 ± 4.27d	37.71 ± 1.46c	32.75 ± 1.18c	41.37 ± 1.03c
300	40.71 ± 1.42b	45.65 ± 1.76b	43.57 ± 1.69b	48.03 ± 1.24b	38.73 ± 1.44b	42.35 ± 1.15c
330	40.94 ± 1.24b	50.59 ± 1.92a	46.5 ± 1.61ab	48.54 ± 1.2b	37.75 ± 1.05b	47.35 ± 1.14b
360	49.22 ± 1.57a	52.15 ± 1.8a	49.76 ± 1.71a	52.67 ± 1.15a	61.29 ± 4a	59.82 ± 1.29a

Different letters in the same column indicate a significant difference at $p < 0.05$.

For the same plant species, the decomposition rate tended to be lower for the branch portion than for the leaf portion, especially during the early stage of decomposition. For the same portion of litter, there was no clear trend showing which plant species had a high decomposition rate during the same period of field incubation; though, during the first two months, the branch of *Kandelia obovata* (Linn.) Druce had a lower decomposition rate as compared to its counterpart of the other two mangrove plant species.

An analysis showed that after the first 30 days of field incubation, over 10% of the added litter was lost except for the branch portion of *Heritiera littoralis* and *Kandelia obovata*. However, the WLR on the 60th day showed no significant increase ($p > 0.05$), as compared to those on the 30th day, respectively. A significant increase in WLR from the 60th to the 90th day was not observed for either the leaf portion of *Heritiera littoralis* or *Kandelia obovata*. There was no significant difference in weight loss rate between the 150th and the 210th day for either the branch or leaf of the *Thespesia populnea* and *Kandelia obovata* (Table 2).

3.3. Organic Carbon in the Soils Underneath the Added Litter Materials

The organic carbon content in the soil samples collected at different time intervals is given in Table 3. On the 90th day of the field incubation experiment, the organic carbon content in the soils under all three mangrove plant species tended to be lower, as compared to their counterpart original soils. The soil-borne organic carbon then markedly increased from the 90th to the 180th day. From the 180th to the 270th day, soil organic carbon content decreased before it increased again until the 360th day.

Table 3. Organic carbon concentration (g/kg) in the surface soil layer (0–5 cm) underneath the added litter for the three selected mangrove plant species.

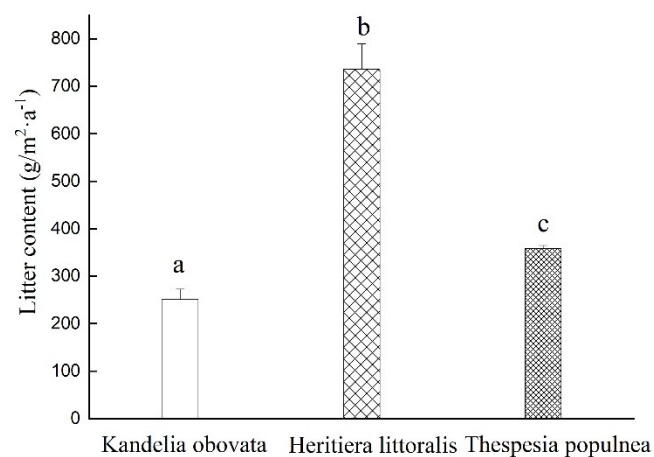
Time (d)	<i>Kandelia obovata</i>	<i>Heritiera littoralis</i>	<i>Thespesia populnea</i>
Original	11.65 ± 2.42a	12.52 ± 4.1a	11.34 ± 1.43b
90	11.32 ± 2.13a	11.34 ± 0.31a	10.39 ± 1.42b
180	13.99 ± 1.21b	13.40 ± 2.18ab	13.42 ± 0.51a
270	13.82 ± 3.01b	12.28 ± 1.34ab	11.56 ± 0.52b
360	16.29 ± 0.29b	14.89 ± 1.68b	14.56 ± 0.7a

Different letters in the same column indicate a significant difference at $p < 0.05$.

4. Discussion

The field monitoring results suggest that the litter yield was subject to seasonal control (Figure 2). Autumn was the major period of litterfall following the strong growth period starting from late spring. Due to the low temperatures in winter, biomass production was low, leading to the low recorded litter yield. The litter yield increased after spring arrived as a result of enhanced biomass production for *Heritiera littoralis* and *Kandelia obovata*. The lack of other litterfall peaks for *Thespesia populnea* indicated that this species had a longer leaf life span, as compared to the other species. It has been established that different plants have different leaf senescence and fall dynamics [26,27].

Amongst the three investigated mangrove species, the annual litter yield was in the following decreasing order: *Heritiera littoralis* > *Thespesia populnea* > *Kandelia obovata* (Figure 3). Mangrove litter yield is directly related to geographical environment, species, and tree maturity [28]. The *Heritiera littoralis* had a larger average diameter at breast height (DBH), average tree height, and tree canopy cover, as compared to the other two species. This might be partly responsible for its highest annual litter yield.

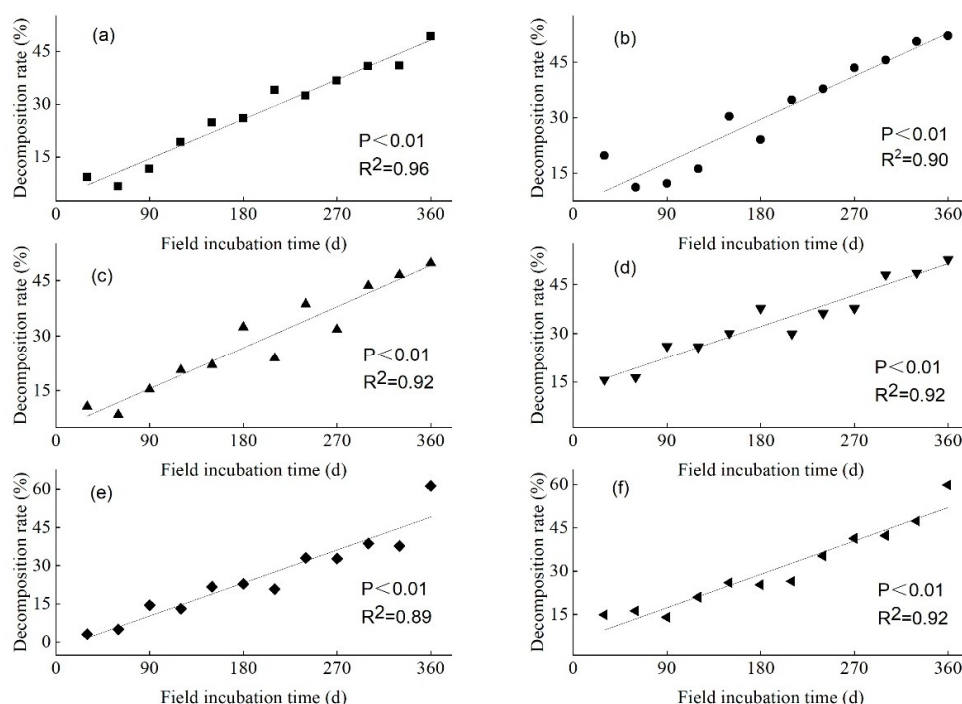
**Figure 3.** A comparison of litter yield among the three mangrove species.

The highest annual litter yield (745 g m⁻²) of the *Heritiera littoralis* is comparable to the annual litter yield for the same species at other locations along the South China coast (Table 4). It is interesting to note that the investigated *Heritiera littoralis* was much younger than that at the Jiulong Estuary and in Shenzhen. This suggests that tree age may play a weak role in affecting the litter yield when the mangrove tree reaches an age of nearly 10 years old.

Table 4. A comparison of annual litter yield of *Heritiera littoralis* at different locations along the South China coast.

Location	Tree Age (year)	Tree Height (m)	Litter Yield (g m^{-2})	Literature Source
Zhuhai, China (22°23' N; 113°36' E)	9	5.5	745	This study
Jiulong Estuary, Fujian, China (24°24' N; 117°55' E)	30	6	863	[29]
Nansha, Guangzhou, China (23°01' N; 113°41' E)	-	-	460	[30]
Shenzhen, China (22°31' N; 114°00' E)	30	6.3	603	[31]
Leizhou Peninsula, China (20°41' N; 110°12' E)	-	-	848	[32]

The marked weight loss of the added mangrove litter within the initial 30 days was likely to be the result of rapid decomposition of the easily degradable component of the litter materials. The observed phenomenon of a higher WLR for shorter periods of incubation, relative to that for longer periods of incubation for some occasions, suggests that the environmental conditions for the 12 spots where the mangrove litter was placed on the soil for observing the effects of time on the litter decomposition were not consistent. This makes it inappropriate to use the data to illustrate the progressive decomposition of the mangrove litter during the monitoring period. However, as shown in Figure 4, there was a good linear relationship between the length of field incubation time and the litter decomposition rate for both the branch and the leaf portion of the three investigated mangrove species.

**Figure 4.** Relationship between the length of field incubation with the decomposition rate of the mangrove litter for (a) the branch of *Heritiera littoralis*; (b) the leaf of *Heritiera littoralis*; (c) the branch of *Thespesia populnea*; (d) the leaf of *Thespesia populnea*; (e) the branch of *Kandelia obovata*; and (f) the leaf of *Kandelia obovata*.

Overall, approximately 50% or more of the added mangrove litter could be decomposed within one year for either the branch portion or the leaf portion of the three investigated mangrove species. This transforms to a litter decomposition rate of over 0.013 g per day. The decomposed litter could be incorporated into the underlying soils and consequently affect the soil carbon dynamics. It is interesting to note that within the initial 30 days of the field incubation experiment, the soil carbon

decreased. This suggests that the carbon input, if any, into the soils from the decomposing mangrove litter was less than the carbon output from the soils due to decomposition of the soil-borne organic carbon. This might be due to the fact that the products of litter decomposition at the initial stage were mainly of highly soluble low-molecular-weight organic acids that were not retained by the soils [33,34].

The increase in soil organic carbon content from the 90th to the 180th day may be attributed to the slowing mineralization of soil organic carbon due to reduced microbial activities under winter conditions. After winter, the mineralization of soil organic matter increased as a result of increasing temperature, leading to the exceedance of soil carbon loss over the soil carbon input. This may explain the decrease in soil organic carbon from the 180th to the 270th day. The marked increase in soil organic carbon from the 270th to the 360th day probably reflects the increased input of soil organic carbon from the decomposing mangrove litter because of the increasing production of high-molecular-weight organic acids, which tended to be recalcitrant to rapid decomposition. The formation of humic substances allowed for the retention of soil organic carbon.

Under the field incubation conditions, an annual soil carbon increase from 2.37 to 4.64 g/kg in the top 5 cm of the soil was recorded for the investigated mangrove species. This transforms into an annual soil carbon capturing of 3.61 t C/ha for *Heritiera littoralis*, 2.41 t C/ha for *Kandelia obovata*, and 2.39 t C/ha for *Thespesia populnea*. There are approximately 22,260 ha of barren mudflats along the South China coast. Therefore, some 154,518 to 233,392 tons of carbon could potentially be sequestered through mangrove planting in the mudflats.

5. Conclusions

Litter yield of the mangrove species was subject to seasonal control. The annual litter production was in the following decreasing order: *Heritiera littoralis* > *Thespesia populnea* > *Kandelia obovata*. The rapid decomposition of easily degradable components of the litter materials resulted in marked weight loss of the mangrove litter within the initial 30 days. There was a good linear relationship between the length of field incubation time and the litter decomposition rate for both the branch and the leaf portion of the three investigated mangrove species. About 50% or more of the added mangrove litter could be decomposed within one year. The organic colloids derived from litter decomposition could be incorporated into the underlying soils and consequently affect the soil carbon dynamics and result in soil carbon sequestration.

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